

# An HST Snapshot Survey of Proto-Planetary Nebulae Candidates: Two Types of Axisymmetric Reflection Nebulosities

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## ABSTRACT

We report the results from an optical imaging survey of proto-planetary nebula candidates using the *Hubble Space Telescope* (*HST*). The goals of the survey were to image low surface brightness optical reflection nebulosities around proto-planetary nebulae and to investigate the distribution of the circumstellar dust, which scatters the star light from the central post-asymptotic giant branch star and creates the optical reflection nebulosities. We exploited the high resolving power and wide dynamic range of *HST* and detected nebulosities in 21 of 27 sources. The reduced and deconvolved images are presented along with photometric and geometric measurements. All detected reflection nebulosities show elongation, and the nebula morphology bifurcates depending on the degree of the central star obscuration. The Star-Obvious Low-level-Elongated (SOLE) nebulae show a bright central star embedded in a faint, extended nebulosity, whereas the DUst-Prominent Longitudinally-EXtended (DUPLEX) nebulae have remarkable bipolar structure with a completely or partially obscured central star. The intrinsic axisymmetry of these proto-planetary nebula reflection nebulosities demonstrates that the axisymmetry frequently found in planetary nebulae predates the proto-planetary nebula phase, confirming previous independent results. We suggest that axisymmetry in proto-planetary nebulae is created by an equatorially enhanced superwind at the end of the asymptotic giant branch phase. We discuss that the apparent morphological dichotomy is caused by a difference in the optical thickness of the circumstellar dust/gas shell with a differing equator-to-pole density contrast. Moreover, we show that SOLE and DUPLEX nebulae are physically distinct types of proto-planetary nebulae, with a suggestion that higher mass progenitor AGB stars are more likely to become DUPLEX proto-planetary nebulae.

*Subject headings:* stars: AGB and post-AGB — stars: mass loss — planetary nebulae: general — reflection nebulae

## 1. Introduction

Intermediate mass stars (initial main sequence mass of  $0.8 - 8.0M_{\odot}$ ) evolve through a transitional proto-planetary nebula (PPN) phase between the asymptotic giant branch (AGB) and planetary nebula (PN) phases (Iben & Renzini 1983). A PPN consists of a cool ( $T_{\text{eff}} \lesssim 10^4$  K) post-AGB stellar core and an extensive circumstellar shell of gas and dust, which is the former stellar envelope ejected through wind mass

loss<sup>1</sup>. In the PPN phase, AGB mass loss is assumed to have ceased but photoionization of circumstellar matter is considered not to have been initiated (cf. Kwok 1993). The PPN phase is still poorly studied because PPNe are statistically rare objects in the sky due to (1) their characteristically short time scale of evolution ( $\sim 10^3$  years) with respect to a typical AGB evolutionary time scale ( $\sim 10^6$  years) and (2) technological constraints imposed by PPNe’s small angular scale and the presence of dust grains. Despite this rarity, approximately 100 PPN candidates have been identified from optical and infrared studies (e.g., Hrivnak, Kwok, & Volk 1989, Oudmaijer et al. 1992).

One of the most significant changes that occurs to stars during the transition is the emergence of axisymmetry. It is observationally established that most OH/IR stars, whose stellar cores are AGB stars (Goldreich & Scoville 1976), show a high degree of spherical symmetry (cf. Habing & Blommaert 1993), while most (80%) planetary nebulae display either bipolar or elliptical symmetry<sup>2</sup> (Zuckerman & Aller 1986). Therefore, the departure from spherical symmetry must take place somewhere along the evolutionary sequence between the two phases. The aspherical shaping of PNe has been qualitatively explained by the interacting stellar winds (ISW) model. In this framework, the fast wind ( $\gtrsim 10^3$  km/s) is expected to “snow plow” slowly coasting ( $\gtrsim 10$  km/s) circumstellar material which was ejected from the stellar envelope during the previous mass loss epoch (Kwok 1982). Then, axisymmetry can be imposed by introducing the notion of the equatorial density enhancement in the mass loss ejecta (Kahn & West 1985) and distinct morphological groups can be created by varying the degree of equatorial enhancement in red giant or AGB ejecta (e.g., Balick 1987, Habing et al. 1989, Mellema & Frank 1995). Although there has been a number of suggestions for the source of equatorial density enhancement (which includes magnetic fields and binary companions to name a few; e.g., Soker 1998, Mastrodemos & Morris 1999), there is no definite solution to the problem. Whichever the true scenario may be, a significant portion of the entire mass loss history is imprinted on the PPN circumstellar shell of gas and dust: the innermost edge defines the termination of mass loss and the mass loss history can be traced back in time as one probes outer regions of the circumstellar shell. Therefore, one can investigate when and how geometry of mass loss departs from spherical symmetry by sampling dust/gas distribution at various radial locations in a PPN circumstellar shell. One must, however, employ techniques that are sensitive to neutral gas (molecular line emission in radio) and dust (thermal emission in infrared and scattering of star light in visible) since no photoionization has taken place in the PPN circumstellar shell.

In order to sample the most recent mass loss history one needs to probe the innermost regions of a PPN circumstellar shell. Previous ground-based investigations of PPN circumstellar shells include mid-infrared imaging of the thermal emission from warm ( $\sim 100$ K) dust grains (e.g., Meixner et al. 1999), optical imaging of the reflection nebulosity (e.g., Hrivnak et al. 1999b), and spectropolarimetry of the dust-scattered star light (Schmidt & Cohen 1981, Johnson & Jones 1991; Trammell, Dinerstein, & Goodrich 1994, hereafter TDG94). All of these studies have shown the axisymmetric nature of the innermost regions of PPN circumstellar shells. Recent work on HST imaging of PPNe (Egg Nebula, Sahai et al. 1998; *IRAS* 17150–3224, Kwok, Su, & Hrivnak 1998; *IRAS* 17441–2411, Su et al. 1998) have displayed spectacular images of bipolar reflection nebulosity but concentrated on a few PPNe that are associated with mostly or entirely obscured central stars. Our *HST* survey of PPNe covers a larger number of targets than any of the previous studies and, more importantly, includes PPNe candidates that are associated with bright central

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<sup>1</sup>We reserve the word “shell” to refer to the circumstellar material that is physically detached from the central star to avoid confusion with the word “envelope,” with which we refer to the mantle of a star.

<sup>2</sup>We consider bipolar and elliptical morphologies form mutually exclusive sets (see discussions below).

stars.

Our main goal in this survey is to detect small and faint reflection nebulosities around PPN candidates at various evolutionary stages and to investigate if there exists any coherent morphological trend that will bridge gaps between the circumstellar shell morphologies in the AGB and PN phases. In this paper, we report results of our survey of optical reflection nebulosities around 27 PPN candidates, in which the high resolving power and wide dynamic range of *HST* are both exploited to the fullest extent. In the following sections, procedures of observations and data reduction are summarized (§2), results are presented (§3), and the physical nature of morphological groups that we find and the subsequent implications in the context of the PPN evolution are discussed (§4) with conclusions (§5).

## 2. Observations

### 2.1. Modes of Observation

The 27 PPN candidates were observed with the Wide Field and Planetary Camera 2 (WFPC2) on-board *HST* between 1996 April and 1997 August (Program IDs 6364 and 6737) and were all acquired in the Planetary Camera (PC) chip ( $f/28.3$ ,  $0''.0455$  pixel $^{-1}$ ). Observed coordinates for each object are listed in Tables 1, 2, and 3.

To obtain high resolution images, each source was observed with a two- or three-point linear dithering pattern (the telescope is linearly shifted with a non-integer multiple of pixels). The dithering technique is now widely used in WFPC2 observations to fully exploit the high resolving power of *HST* from undersampled WFPC2 images. In conjunction with the dithering, the objects were observed with a set of different exposure times to cover the wide dynamic range that we required in our images. To image faint nebulosities with a sufficiently high signal-to-noise ratio, observations were made with intentionally long exposure times. For example, *IRAS* 22272+5435 was observed with 0.11, 1.2, 16, and 120 sec exposures. As a consequence, pixels in the vicinity of the central star were often saturated or contaminated by anomalies (e.g., bleeding, ghosts). The short exposure frames, which would be free of saturated pixels, were used to recover the loss of information in such pixels. In order to maximize the coverage of the dynamic range, we used a gain of 15 electrons per Data Number (DN) in our observations.

We typically used two wide band filters, F555W and F814W (WFPC2 equivalent of the Johnson-Cousins bands,  $V_J$  and  $I_C$ ; e.g. Holtzman et al. 1995), for each source. However, F450W (Wide B) filter was used when a source had previously been observed with F555W. For extremely bright sources, we used medium and narrow band filters, F410M (Strömgren  $v$ ), F547M (Strömgren  $y$ ), and F469N (He II), to avoid saturation in the shortest exposure frames. In total, approximately a dozen raw images were obtained for each source and filter.

### 2.2. Data Reduction

We used IRAF/STSDAS routines in data reduction. A standard *HST* pipeline calibration was performed with the latest reference files available at the time of data reduction. Duplicate frames of dithered images were combined into a single image by applying the variable-pixel linear reconstruction algorithm (“drizzle” package v1.2, Fruchter & Hook 1997), which would interlace each pixel in multi-point dithered frames according to the statistical significance of each pixel. The drizzled images were subpixelized

( $0''.0228 \text{ pixel}^{-1}$ ) during the process and thus the high spatial resolution was recovered. Cosmic-rays were removed by the drizzling algorithm in the three-point dithered frames, while they were eliminated manually by replacing the contaminated pixels with a median of the neighboring pixels in the two-point dithered frames.

In order to create non-saturated final source images, the saturated and unsaturated frames were combined by replacing saturated pixels with unsaturated ones from the shorter exposures, scaled by the exposure times. We have thus successfully obtained high dynamic range images of reflection nebulosities whose outer perimeters often seem to be sky-limited. Figures 1, 2, and 3 show the reduced images. The resulting nebular signal-to-noise ratio ranges from  $\lesssim 2$  for a faint nebula to  $> 100$  for a bright nebula, while the star-to-nebula ratio, which quantifies the emission contrast between the central star and nebulosity as a measure of the dynamic range, ranges from 18 for a compact nebula up to  $1.8 \times 10^5$  for an extended nebula. Some faint nebulae are barely distinguishable from the background sky, while some others are almost buried under the point spread function (PSF) of the central star itself.

### 2.3. Image Enhancements

The reduced images, particularly those with a bright central star, were affected by the WFPC2 diffraction patterns that consist of linear spikes and circular wings. We employed image enhancement techniques to remove unwanted effects of the WFPC2 point spread function (PSF) so that the reflection nebulae would be more clearly seen. One could remove the effects of the WFPC2 PSF by either (1) subtracting a stellar PSF from a source image or (2) deconvolving a source image with a stellar PSF.

A PSF subtraction can be done with either an observed PSF or a synthesized PSF. Although observed PSFs were often preferred (Krist et al. 1997), we used synthesized PSFs because there existed no PSF with a high enough dynamic range in proper filters for our observations. Model WFPC2 PSFs were generated by the code Tiny Tim (v4.4, Krist & Hook 1997) for a given mode of observation, but the PSF had to be scaled to account for the drizzling.

Alternatively, a deconvolution technique can be used to eliminate the PSF effects in the reduced source images. We used the Richardson-Lucy (RL) algorithm and maximum entropy method and the former generally yielded better results than the latter. This suggests that the most significant noise in our images was due to photon shot noise because iterative solutions yielded by the RL algorithm are known to converge into the maximum likelihood solution in Poisson statistics (Shepp & Vardi 1982). In general, the contrast between the nebula and sky emission at the outer perimeter of a nebula was increased by a factor of  $\gtrsim 2$ ; however, there seemed to be little improvement in a few very extended nebulosities where the nebula emission was comparable to the sky emission. Unlike the case of PSF subtraction, a deconvolution technique could be applied to all our images. One shortcoming in RL deconvolution is that the algorithm is known to amplify uncertainties and generate false depressions around pixels with unusually high DNs, and such “holes” indeed appeared in the deconvolved images. Therefore, we have to keep in mind that any interior structure in the deconvolved images should be regarded as suspect.

Overall, we found that the RL deconvolved images provided the best removal of the PSF effects among all the methods we tried. Thus, we present only the RL deconvolved images alongside the original reduced images in Figures 1, 2, and 3.

## 2.4. Measurements

Photometric and geometric quantities were measured from the reduced source images. To give the total specific flux density ( $F_\lambda$  in  $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ ), the reduced images were flux calibrated by adopting the *HST* photometric calibration of SYNPHOT (v4.0, Simon 1997). First, we defined a photometric aperture that was large enough to encircle the entire source as well as the diffraction features. The total DN of a source was then determined by summing all DNs within the aperture. The background emission per pixel was estimated by calculating the averaged sky DN inside a 10-pixel-wide annulus that encloses the aperture but was separated from the aperture by a buffer zone. The background DN, which is the averaged sky DN multiplied by the number of pixels in the aperture, was subtracted from the total DN only when the averaged sky DN per pixel was greater than the root mean square of the sky DNs in the background annulus because otherwise the background subtraction would introduce an additional  $1\sigma$  uncertainty to the results. We expect that an uncertainty due to the background subtraction is rather insignificant because considerably larger DNs in the emission core will dominate the total emission of the source and thus photon shot noise will dominate. The total source DN was then converted into  $F_\lambda$  and the WFPC2 system magnitude (STMAG).

The extent of the nebulosities was estimated from the images by defining the “edge” of a nebula to be the outermost recognizable structure, in which the emission level turned out to be  $1\sigma$  up to about  $7\sigma$  of the sky depending on the quality of the image. The major and minor axes of the nebula were measured and the ellipticity of a nebula was derived by  $e = 1 - b/a$  ( $a$  and  $b$  are respectively major and minor axis lengths). With the edge of a nebula being defined, we can also measure the surface intensity ( $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1} \text{sr}^{-1}$ ) at the peak and edge of the nebula, from which we can obtain the star-to-nebula surface intensity ratio as a measure of the width of the dynamic range covered by the image. When the central star is visible, the peak coincides with the location of the central star, but, when the central star is totally obscured, the peak is simply the local maximum in the emission region. All derived quantities are summarized in Tables 1, 2, and 3.

## 3. Results

### 3.1. Images of Reflection Nebulosity

Of 27 PPN candidates, 21 were found with fascinating reflection nebulosities around the central stars and six did not seem to be associated with any nebulosity. By inspection, one immediately realizes the following: (1) all 21 nebulae show asphericity with varying degrees and (2) there clearly exist two types of axisymmetry among those aspherical nebulosities. One type of nebulosity is characterized by its very low surface brightness and multi-axis elongations which surround extremely bright central stars. The other type, however, is distinguished by the limb-brightened bipolar lobes with their partially or completely invisible central stars somewhere in the nebulae. Because this apparent bifurcation is so astonishing in the morphology of reflection nebulosity, we categorize the two types according to the traits in appearance described above and refer to the former type as the Star-Obvious Low-level-Elongated (SOLE) nebulae while the latter type as the DUst-Prominent Longitudinally-EXTended (DUPLEX) nebulae. Among 21 nebulosities, 11 and 10 are respectively found to be SOLE and DUPLEX nebulae in this classification.

One of the key differences between SOLE and DUPLEX sources is the star-to-nebula surface intensity ratio (Table 1 and 2), which is a useful quantity to estimate the size of the dynamic range required to

observe SOLE nebulae. For sources with the visible central star (all SOLE and DUPLEX nebulae with the partially visible central star), the dynamic range varies from 18 (for the most compact SOLE source, *IRAS* 07430+1115) to  $1.8 \times 10^5$  (for the most extended SOLE source, *IRAS* 19114+0002) with the average value of  $1.3 \times 10^4$ . On the other hand, for sources with the obscured central star (bipolar DUPLEX nebulae), the dynamic range is at most 330 (*IRAS* 20028+3910, whose northern lobe is barely detected) with the average value of 55. In recent subarcsecond optical imaging of PPNe by ground-based telescopes, four of our sources (*IRAS* 18095+2704, *IRAS* 19374+2359, *IRAS* 20028+3910, and *IRAS* 22574+6609) were observed to determine their morphology (Hrivnak et al. 1999b). However, they were unable to determine if *IRAS* 18095+2704 (the only SOLE source among the four) is extended partly due to the brightness of the star ( $V = 10.3$ ) despite the suggestion of its extension from the FWHM of their  $V$  image. Because of the wide dynamic range we achieved ( $\sim 1000$ ), our *IRAS* 18095+2704 images clearly show that it is indeed an extended source. Therefore, to detect and image faint, extended reflection nebulosities around a bright central star, i.e., the SOLE nebula, a very wide dynamic range must be used. Even the six orders of magnitude coverage barely detects the outermost structure in images of *IRAS* 19114+0002 and there may be even fainter, more extended nebulosity.

Although we classify the objects mainly on morphological grounds, spectral energy distribution (SED) and two-color diagrams provide supplemental information to determine the morphological class of an object. The sources that are not considered to be associated with any nebulosities are referred to as stellar sources (see discussions below). We adopt these terms to address each morphological type hereafter and will discuss the morphological dichotomy in detail in the following subsections. Figures 1(a) to 1(c), 2(a) to 2(c), and 3 show SOLE, DUPLEX, and stellar sources, respectively<sup>3</sup>.

### 3.1.1. SOLE Nebulae

The SOLE nebulae show the very bright central star embedded in a very low surface brightness nebulosity (Fig. 1). This type of reflection nebulae has been imaged for the first time by this survey: the central star is so bright that the object would always appear as a point source unless the observations are done with the high enough resolution (available with *HST*) and/or wide enough dynamic range (available with our method of multiple exposure times). The very eye-catching trident-like structures emanating from the central star are WFPC2 linear diffraction spikes and are not to be construed as real structure. The reader is encouraged to compare the images of the SOLE nebulae (Fig. 1) with those of the stellar sources (Fig. 3) to help the eye differentiate real structures from remnants of the PSF artifacts such as the diffraction spikes and circular halos. The morphology of the SOLE nebulae can be further subdivided into groups: a simple ellipse, multiple ellipses (more than one ellipse superposed onto one another with differing orientations of the major axes), an ellipse with embedded bipolar structure, and an ellipse with concentric shells.

*IRAS* 07134+1005, *IRAS* 17436+5003, and *IRAS* 20462+3416 all have large ( $\lesssim 4''$ ) and faint nebulosities. The size of the optical reflection nebulosity in *IRAS* 07134+1005 is the largest among the  $21\mu\text{m}$  feature sources (e.g. Hrivnak & Kwok 1991a) and is comparable to mid-infrared images (Meixner et al. 1997). The extended nature of *IRAS* 17436+5003 was suspected from wings of  $^{12}\text{CO}$  ( $J=2-1$ ) and  $^{13}\text{CO}$  ( $J=2-1$ ) line profiles (Bujarrabal, Alcolea & Planesas 1992). *IRAS* 20462+3416, a young PN which has

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<sup>3</sup>All fully reduced and deconvolved images are also available in FITS format on the World Wide Web's NCSA Astronomy Digital Image Library (ADIL, at <http://imaginglib.ncsa.uiuc.edu/document/99.TU.01/>).

already started showing low extinction characteristics (Parthasarathy 1993, Smith & Lambert 1994), was observed to have experienced a brief period of an enhanced mass loss between 1993 and 1995 (García-Lario et al. 1997b). *IRAS* 02229+6208 and *IRAS* 07430+1115 have smaller ( $2''$  and  $1''$ ) nebulae. Both of these sources, along with *IRAS* 05341+0852, have recently been observed by Hrivnak & Kwok (1999), but they were unable to determine if the sources are extended due to poor seeing. *IRAS* 04296+3429, *IRAS* 05341+0852, and *IRAS* 22272+5435 have two axes of elongation that are not perpendicular to each other. Despite a circular nebula prediction because of its shape of the SED (Hrivnak & Kwok 1991a, Hrivnak et al. 1999b), *IRAS* 04296+3429 shows a complex double-elongation structure: the secondary E-W elongation of *IRAS* 04296+3429 is close to but not aligned with a diffraction spike and is likely to be real. This is, however, consistent with a suggestion that the source is associated with axisymmetrically distributed, optically thin dust (TDG94). *IRAS* 05341+0852 shows a diffuse elongation in the NE-SW direction and there seems to be a secondary elongation inside of and tilted about  $20^\circ$  counter-clockwise from the primary one. *IRAS* 22272+5435, whose axisymmetric nature was already seen by spectropolarimetry (TDG94), has a bright, large core with the four elliptical tips which create an almost amoeba-like appearance for the nebula. The northern and southern elliptical tips are of equal brightness, but the western tip is 2.6 times fainter than the eastern tip, which is approximately 1.6 times brighter than the northern and southern tips: this suggests that the E-W elongation is tilted (with the eastern lobe being closer to us) but the N-S elongation is not tilted.

*IRAS* 06530–0213 and *IRAS* 18095+2704 have rather peculiar structures. In addition to the well-defined elongation, both sources display an inner structure, which seems to be a limb-brightened bipolar lobes. *IRAS* 18095+2704 shows a similar spectropolarimetric trend as seen in *IRAS* 04296+3429 (TDG94), which may be related to a secondary jet-like structure that extends in the NE-SW direction. However, its very bright central star ( $V_{\text{WFPC2}} = 10.30$ ) and poor seeing prevented Hrivnak et al. (1999) from resolving its extension. *IRAS* 19114+0002 shows rich structure: there are at least four inner concentric shells ( $11''$ ,  $7''$ ,  $4''$ , and  $3''$ ) with some protuberance and one very sharp elongation ( $8''.5$ ) about  $15^\circ$  East from North. The  $^{12}\text{CO}$  ( $J=2-1$ ) map shows very extended structure, which seems to have been shifting its direction: 10% contour points to  $72^\circ$  East from North ( $37''$ ), while 50% contour points to  $45^\circ$  East from North ( $18''$ ). The protuberance seen in our images may have emanated from the same rotating point of origin. The axisymmetric nature has also been seen in polarimetric observations (TDG94). Although the sharp elongation suggests a rather large inclination angle, *IRAS* 19114+0002 is believed to be close to a pole-on orientation, which is evidenced by a hollow shell structure seen in both mid-infrared (Hawkins et al. 1995) and near-infrared polarimetric (Kastner & Weintraub 1995) imaging studies.

### 3.1.2. DUPLEX Nebulae

The DUPLEX nebulae are recognized either by their magnificent bipolar nebulosities or by rather well-defined limb-brightened bipolar lobes (Fig. 2). They are usually outlined by a lower surface brightness halo. These nebulae differ from the SOLE nebulae in appearance primarily because their central stars are partially or completely obscured. The diffraction spikes are not usually an issue in the images of DUPLEX nebulae as the central stars are obscured from the direct view. The DUPLEX nebulae can also be further subdivided into two groups depending on the presence or absence of the central star.

*IRAS* 16342–3814, *IRAS* 17150–3224, *IRAS* 17441–2411, *IRAS* 20028+3910, and *IRAS* 22574+6609 show multiple emission peaks without clear indications of the central star’s whereabouts. Among those, *IRAS* 17150–3224 and *IRAS* 17441–2411 are found with comparable lobes both in size and brightness

and their lobes possess some inner structure that seems to be point symmetric. There are also thin concentric arcs extending beyond the perimeters of the lobes. The arcs appear to be created independently of the lobes because the arcs maintain the same emission level both in and out of the lobes and hence seem to be unaffected by the presence of the lobes. The intervals between arcs have been estimated to be too short to be caused by the consecutive AGB thermal pulses (Paczynski 1975). Our *B* and *I* band images of *IRAS* 17150–3224 and *IRAS* 17441–2411 confirm the findings by previous *HST* wide *V* band observations (Kwok, Su, & Hrivnak 1998, Su et al. 1998). Weintraub et al. (1998) obtained  $\text{H}_2$  emission profiles from these sources and confirmed their orientations suggested from the *HST* optical images. They even also found evidence of an expanding torus in *IRAS* 17150–3224, which was shown in a *V–I* image constructed from ground-based observations (Kwok et al. 1996). *IRAS* 16342–3814 and *IRAS* 20028+3910 have unequal lobes in which some inner structure is recognized in the primary lobe. The bipolar nature of *IRAS* 16342–3814, an extreme AGB star, was revealed in  $\text{H}_2\text{O}$  and  $\text{OH}$  maser observations (Likkell & Morris 1988), and recent VLA observations of  $\text{OH}$  maser determined its inclination angle to be about  $40^\circ$  (Sahai et al. 1999). *IRAS* 20028+3910 has recently been reported to be extended ( $2''.2 \times 2''.0$ , Hrivnak et al. 1999b), but this only corresponds to the S lobe (which is about 25 times brighter than the N lobe) of this bi-lobal object. Interestingly, the deconvolved images of *IRAS* 20028+3910 show multiple-peaks within the S lobe. *IRAS* 22574+6609 is optically resolved for the first time and the images indicate the presence of more than two emission peaks, confirming an earlier suggestion of elongation (Hrivnak & Kwok 1999a). The emission level of the suspected third emission peak ( $0''.2$  north of the second peak) is almost the same as that of the background sky and thus its presence is inconclusive. This “third” peak may simply be a part of a clumpy second peak, in which case the overall appearance of the source resembles that of *IRAS* 17441–2411. Our *V* band photometry ( $V_{\text{WFPC2}} = 21.24$ ) differs from that of Hrivnak & Kwok (1991a;  $V_J = 24$ ). This difference is significant enough to mention, even though we are comparing magnitudes in slightly different systems. Their lower magnitude suggests that it may have been affected by the unusually poor seeing (Hrivnak & Kwok 1991a), or this star may have been experiencing a significant brightening.

*IRAS* 08005–2356, *IRAS* 17423–1755, and *IRAS* 19374+2359 have the partially visible central star with limb-brightened bipolar lobes which appear as a pair of horseshoe structures facing each other along the bipolar axis. Slijkhuis et al. (1991) observed an unusually broad  $\text{H}\alpha$  line profile in *IRAS* 08005–2356 and attributed it to a fairly extended emission region. This interpretation is independently supported by spectropolarimetry, which shows an abrupt position angle shift suggesting an optically thick dust torus and optically thin reflection lobes (TDG94). Both of the above views are confirmed by the bipolar shape clearly seen in our images. Its SE lobe is approximately 3 times brighter than the NW lobe, which suggests that the SE lobe is tilted towards us so that the central star becomes partially visible within the conical opening angle of the lobe. *IRAS* 17423–1755 displays fascinating point symmetric jet-like structures extending  $17''$  in the whole stretch. The NW lobe is more prominent (8 times brighter) than the SE lobe, whose presence can be traced with the help of the slightly visible, outer part of the limb. This suggests that the NW lobe is inclined towards us, again explaining the partial view of the central star. The way the SE lobe is obscured strongly suggests the presence of a dust torus between the lobes. This interpretation agrees with a model in an earlier multi-wavelengths study, in which fast, collimated jets punctured a detached shell causing a torus-like shell structure (Bobrowsky et al. 1995). Although less prominent, there are at least three knots in each of the point symmetric jets as seen previously (Bobrowsky et al. 1995, Riera et al. 1995, Borkowski, Blondin, & Harrington 1997). A hydrodynamic simulation shows a diverging outflow being focused into a narrow jet and the point symmetric structure can be explained by wobbling jets (Borkowski, Blondin, & Harrington 1997). *IRAS* 19374+2359 was observed by Hrivnak et al. (1999b) and a round extension ( $2''.6$ ) is seen. This corresponds to the outer halo in our images. Although our images of *IRAS* 19374+2359 have

smaller signal-to-noise ratio compared with other images, one can discern the star from the nebula in the northern lobe, which is 3 times brighter than the southern counterpart, suggesting that the northern lobe is pointing towards us.

The two remaining DUPLEX sources, *IRAS* 09452+1330 (*IRC*+10216) and *IRAS* 23321+6545, do not neatly fit into either of the above subdivisions. *IRAS* 09452+1330 is the best studied C-rich AGB star in the Galaxy. The *I* band image was previously published (Skinner, Meixner, & Bobrowsky 1998) and is included in this survey for the sake of completeness. The aspherical appearance of *IRAS* 09452+1330 has been interpreted as a bipolar nebula whose southern lobe is pointed towards us, being separated from smaller northern lobes by a dust lane, and the bright point-like source in the southern lobe may be the central star (Skinner, Meixner, & Bobrowsky 1998). Thus, we classify *IRAS* 09452+1330 as a DUPLEX source because its reflection nebulosity appears quite similar to that of DUPLEX PPNe. We also observed the source with the wide B filter but did not detect anything. The optical counterpart to *IRAS* 23321+6545 is imaged for the first time. Its very small spatial extent suggests that this object is located relatively far away. However, the fact that this distant source appears extended alternatively indicates that the nebulosity has rather high surface brightness compared to the central star, which is a typical characteristic of DUPLEX nebulae. If *IRAS* 23321+6545 were a SOLE nebula, the PSF of the bright central star would have masked any structure of the fainter, compact nebula and the source would have appeared as a point source. Therefore, *IRAS* 23321+6545 must possess DUPLEX structure, possibly the one with the partially visible central star.

### 3.1.3. Stellar Sources

Figure 3 shows the sources lacking clear indications of the presence of a nebulosity. *IRAS* 04386+5722, *IRAS* 20043+2653, and *IRAS* 22142+5206 only have the diffraction features and no evidence of extended emission regions. There is no deconvolved image displayed for both *IRAS* 20043+2653 and *IRAS* 22142+5206 because all of the frames were saturated and reconstruction of the non-saturated peaks was not possible. Ghosts appear in the images of *IRAS* 04386+5722 as the “double dots” about 2'' east of the star: they are double because each ghost appeared at different chip locations in the dithered frames. *IRAS* 05113+1347 does not seem to have any extended nebula, however, the deconvolved images leave rather high residual DNs within 0''.4 of the central star where a Tiny Tim PSF is able to simulate PSF effects rather well (Krist et al. 1997). Because of its small angular extent, it is inconclusive whether this is real or not. *IRAS* 10158–2844 and *IRAS* 15465+2818 are considered to have had little recent mass loss but are associated with very diffuse, extended circumstellar dust shells (Gillett et al. 1986, Waters et al. 1989). Our images are consistent with this picture of little mass loss by showing no apparent nebulosity. Because these stars are very bright (hence the use of a narrow band filter), the diffraction features are more prominent in these images than in other images.

## 3.2. Measured Quantities and Binary Companions

Tables 1, 2, and 3 summarize the measured quantities for SOLE, DUPLEX, and stellar sources, respectively. The quantities are the total specific flux densities ( $F_\lambda$  in  $\text{ergs s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$ ), WFPC2 system magnitudes (STMAG), peak intensities, star-to-nebula intensity ratios, sizes, and ellipticity. Table 2 is subdivided into two sections according to the visibility of the central star: the peak intensity represents the intensity of the star when the location of the central star in the nebula is certain (top 4 objects) whereas

it represents the local intensity maximum in the emission region when the central star is completely or partially obscured (the rest). For images that show clear bipolar structure with halo, the size and ellipticity are measured for the entire halo as well as for each lobe. We only list photometric quantities for stellar sources (Table3).

All  $V_{\text{WFPC2}}$  are generally in good agreement with the previously published  $V_J$  in the literature ( $|\delta V| \approx 0.18$  mag) where the STMAG closely resembles the Johnson system, except for two sources (*IRAS* 16342–3814 and *IRAS* 22574+6609). Comparison between  $I_{\text{WFPC2}}$  and available  $I_C$  in the literature suggests that  $I_{\text{WFPC2}}$  is generally  $\sim 1.3$  dimmer than  $I_C$ . This offset is due to the definition of STMAG system and the amount of offset is about equal to what is expected by definition in SYNPHOT (Simon 1997). Similarly, magnitudes obtained with other filters deviate from the values in the literature due to the definition of the STMAG system.

Our  $V_{\text{WFPC2}}$  of *IRAS* 16342–3814 (15.64) agrees with another measurement independently made by Sahai et al. (1999) from the same image (15.7). However, these values are significantly dimmer than the value reported in a PPN photometric survey (13.65; Van der Veen, Habing & Geballe 1989, hereafter VH89). A large photometric aperture used by them is suspected to have included nearby bright stars (Sahai et al. 1999). On the other hand, their near-infrared photometric values ( $J=12.17$ ,  $H=10.75$ ,  $K=9.61$ , done in 1986; VH89) are significantly dimmer than those of yet another PPN photometric survey ( $J=9.29$ ,  $H=8.32$ ,  $K=7.71$ , done in 1993; García-Lario et al. 1997a). Because García-Lario et al. (1997) do not discuss their sources individually or give the observed coordinates, we are unable to assess the cause of the discrepancy. It is very unlikely that the central star of a PPN becomes dimmer in  $V$  and brighter in near-infrared. *IRAS* 22272+5435 is suspected to be a variable star with an almost 1 mag variation (Hrivnak & Kwok 1991b). Our measurement ( $V_{\text{WFPC2}} = 8.63$ ) is consistent with its brightest magnitude. There seems to be no sign of any other unreported variability in our sources.

The size of SOLE nebulae is the major and minor axis lengths of the elliptical elongation whereas the size of DUPLEX nebulae is the extent of the halo. Some SOLE nebulae have two axes of elongation. In such cases, we only list major axis lengths of the two elongations but not the minor axis lengths, though the ellipticity are given for each. The averaged ellipticity is rather high for both SOLE and DUPLEX nebulae (0.45 and 0.43, respectively). Here, the ellipticity is even larger for SOLE nebulae. This quantitatively confirms what we have seen in the images: reflection nebulosities are unquestionably elongated in their apparent shapes.

We can also search for signs of binary companions in the vicinity of the sources, and there are several possible cases. *IRAS* 10158–2844 is seen with a star ( $V_{\text{WFPC2}}$  He II mag = 13.70) which is about  $2''$  east of the source. Although *IRAS* 10158–2844 is known to form a binary system of an orbital period of near 434 days with either a low-mass main sequence star or a white dwarf (Waelkens et al. 1991), this nearby star does not seem to be the companion of the binary system because the separation is too large ( $\approx 1500\text{AU}$ ). Whether or not this nearby star is related to *IRAS* 10158–2844 is also not certain. *IRAS* 19114+0002 has a nearby star seen about  $4.5''$  north of the source at the edge of the faintest nebulosity along one of the saturation spikes. However, the stars do not seem to be related due to rather large distance between the two. *IRAS* 19374+2359 has a nearby star ( $V_{\text{WFPC2}} = 20.39$ ) inside the south lobe about  $1''$  away from the central star, but it is likely to be a foreground or background star because of the low galactic latitude of the source ( $1^\circ$ ). *IRAS* 22142+5206 also has a star ( $V_{\text{WFPC2}} = 20.36$ ) about  $2''$  east of the source, but the nature of the nearby star is not certain. *IRAS* 22142+5206 is now classified as a young stellar object embedded in a massive molecular cloud ( $\sim 7300M_\odot$ ; Dobashi et al. 1998). Their observations indicate that the source is associated with the most massive CO outflow ( $\sim 33M_\odot$ ) reported so far, and this may be

because of the binarity of the source.

## 4. Discussions

### 4.1. Axisymmetry: an Intrinsic Nature of PPNe

We have detected optical reflection nebulosities in 21 sources out of 27 PPN candidates (78%) and all of these 21 PPN reflection nebulosities exhibit some type of axisymmetry with the averaged ellipticity of 0.44. Our direct imaging of reflection nebulosities confirms previously published results in a spectropolarimetric survey of post-AGB stars, which has indirectly shown that 24 of 31 sources (77%) are aspherical (TDG94). As we have discussed in the introduction, previous work in the literature has revealed that most PPN candidates possess axisymmetric nebulosities, and therefore, we conclude that the axisymmetry is an intrinsic trait of the PPN reflection nebulosities. Below, we discuss when this axisymmetry arises along the evolutionary track between the AGB and PN phases and how the two different types of PPN may arise.

It is now generally accepted that the AGB phase is associated with two types of mass loss: an AGB wind ( $\sim 10$  km/s) mass loss phase followed by a briefer but supposedly more violent superwind ( $\sim 20$  km/s) mass loss phase (Renzini 1981). Because the termination of a superwind is considered to be the end of the AGB phase and no significant stellar wind is expected until the initiation of a fast wind (Kwok 1982), the PPN axisymmetry must arise just before the end of the AGB phase. This interpretation is also supported by the fact that mass loss is spherically symmetric in the beginning of the AGB phase (Habing & Blommaert 1993) and that some extreme AGB stars have already departed from spherically symmetric structure (e.g., *IRAS* 16342–3814). It is, therefore, very likely that a superwind is intrinsically axisymmetric and that the onset of a superwind initiates the morphological shift from spherical to axial symmetry in a PPN circumstellar dust/gas shell.

Based on the results of our PPN survey with the above inference, we propose the following evolutionary scenario. In the AGB wind phase, an AGB star loses its mass through a dust-driven AGB wind (Salpeter 1974, Kwok 1975, Netzer & Elitzur 1993) in a largely spherically symmetric manner, creating a spherically symmetric circumstellar AGB wind shell. Towards the end of the AGB phase, some physical mechanism, albeit still unknown, comes to play and starts generating an equatorially density enhanced dust-driven wind, which we call an axisymmetric superwind. The axisymmetric superwind dumps the envelope material of the central AGB star preferentially on the equatorial plane, and a superwind shell with a torus-like density enhancement develops deep within the spherically symmetric AGB wind shell. The equatorial density enhancement in the superwind shell is further strengthened as the star evolves. At the end of the AGB phase, the superwind ceases and defines the inner boundary of a detached circumstellar dust/gas shell, which manifests itself as a mid- to far-infrared excess in the double-peaked SED of a PPN (Kwok 1993).

This two-phased AGB mass loss scenario can be employed to explain an apparent “dust lane” obscuring the central star. In one-dimensional radiation transfer simulations, the superwind shell may be treated as a somewhat *ad hoc* addition to an otherwise spherically symmetric dust shell (e.g., Su et al. 1998). Meixner et al. (1997) have incorporated the two-phased mass loss in fully two-dimensional radiation transfer calculations and their synthesized mid-infrared images and SEDs agree with observations. However, the scenario used in these calculations is still a first order approximation: the transition from a spherically symmetric AGB wind to an axisymmetric superwind is assumed to take place abruptly. Instead, the transition is more likely to occur gradually because mass loss is essentially governed as a function of the fundamental stellar parameters, which do change gradually as the central star evolves if integrated over the

course of the entire AGB phase (e.g., Blöcker 1995).

Given that the details of the two-phased mass loss probably depend on the fundamental stellar parameters, the degree of equatorial density enhancement in a superwind may also be dependent upon them, and the physical environment will probably be distinct in each superwind shell. Figure 4 schematically describes how this can affect the structure of PPN circumstellar shells and may cause the morphological bifurcation of PPN reflection nebulosities. In a SOLE PPN (top), a marginal equatorial enhancement in the superwind shell can yield a dust torus that is optically thin (gray zone), and stellar photons can escape virtually in all directions (arrows). Hence an observer is able to see the bright central star embedded in an elliptically elongated nebula (dashed perimeter). In a DUPLEX PPN (bottom), on the other hand, a stronger equatorial enhancement in the superwind shell can result in an optically thick dust torus (black zone), and most photons are scattered off towards the biconical openings of the torus along its axis of symmetry (arrows), thereby generating a bipolar, dumbbell-like nebulosity (dashed perimeter). When the equatorial enhancement is exceptionally strong, the dust torus can be so flattened that it assumes the form of a thin disk. Therefore, we consider a disk to be an extremely equatorially enhanced torus.

#### 4.2. SOLE vs. DUPLEX: Physically Distinct Nebulae

The distinct appearances between SOLE and DUPLEX nebulae are characterized by the presence or absence of the central star and by the undisturbed elliptical or dumbbell-like outline of the nebulosity. We now discuss how the evident morphological dichotomy of the PPN reflection nebulosities can be caused by a physical difference in the circumstellar dust/gas shell and not by an inclination angle effect alone. More specifically, we propose that the optical morphology of PPN candidates bifurcates because the opacity in the circumstellar dust/gas shells varies due to differing degrees of equatorial density enhancement. Spectropolarimetric survey results of TDG94 show that there are two types of polarization position angle shift (a gradual shift in *IRAS* 04296+3429, a SOLE source and an abrupt shift in *IRAS* 08005–2356, a DUPLEX source) and that the presence of the optically thick and thin, two-component obscuring agent is suspected in PPNe with an abrupt position angle shift. This is consistent with the assumption of DUPLEX nebulae being associated with optically thick dust grains. In the following, we will present three additional pieces of evidence suggesting that the morphological dichotomy indeed corresponds to physically distinct nature of the circumstellar dust shell in PPN nebulae: the mid-infrared morphologies, SEDs, and *IRAS*/near-infrared colors.

##### 4.2.1. Mid-Infrared Morphology of PPN Dust Shells

Meixner et al. (1999) have recently observed 66 PPNe at mid-infrared wavelengths and directly imaged thermal dust emission regions in the circumstellar dust shell. The major discovery in the mid-infrared survey is the morphological bifurcation of dust emission regions: “core/elliptical” types have an extended low emission region surrounding a compact unresolved core, which is attributed to an optically thick equatorial density enhancement, while “toroidal” types show two emission peaks, which are interpreted as limb-brightened peaks of an optically thin, equatorial density enhancement. If we compare the mid-infrared and optical morphologies of PPNe, there is a one-to-one correspondence between the two morphologies

as is shown in Table 4<sup>4</sup>. It appears that toroidals and core/ellipticals are strongly correlated with SOLE and DUPLEX nebulae, respectively. This correlation is consistent with the picture in which a dust optical thickness difference causes the PPN morphological bifurcation. That is, PPN candidates that are optically thin at visible wavelengths (SOLE nebulae) are also optically thin at mid-infrared wavelengths (toroidals), while PPN candidates that are optically thick at visible wavelengths (DUPLEX nebulae) are also optically thick at mid-infrared wavelengths (core/ellipticals).

The ways in which the mid-infrared and optical images are spatially related in SOLE and DUPLEX nebulae differ, and hence, they also suggest a difference in dust shell optical thickness. By direct comparison between the mid-infrared and optical images of SOLE sources, the optical and mid-infrared nebulae are found to be spatially coincident and that the optical nebulosity is elongated perpendicularly with respect to the equatorial plane of the suspected dust torus, whose orientation is indicated by the two mid-infrared emission peaks. In Figure 5, for example, a resolved, deconvolved  $11.8\mu\text{m}$  image of *IRAS* 07134+1005 shows limb-brightened dust emission peaks which are oriented in the east-west direction (Meixner et al. 1997), while its optical (Strömgren  $v$ ) nebula is extended in the north-south direction (top left). A similar trend is seen in the composite image of *IRAS* 17436+5003 (top right; Skinner et al. 1994) as well. On the other hand, the mid-infrared and optical images of DUPLEX sources show elongation in the same direction, and the mid-infrared emission region is often completely embedded within the optical nebulosity. In Figure 5, for example, an  $I$  band image of *IRAS* 17150–3224 clearly displays the dust lane, which completely obscures the central star, between the two lobes and there is a very compact, unresolved mid-infrared emission core over the location of the dust lane (bottom left), and the unresolved dust emission core of *IRAS* 16342–3814 in  $9.8\mu\text{m}$  is very compact with respect to the whole extent of the  $I$  band reflection nebulosity (bottom right).

#### 4.2.2. Spectral Energy Distribution of PPNe

One of the well-established characteristics of PPNe is that their SEDs have a “double-peaked” structure (cf. Kwok 1993). The shortward and longward peaks in the wavelength spectrum respectively correspond to the stellar and dust emission components. The morphological bifurcation between the SOLE and DUPLEX nebulae also manifest itself as a distinction between the SED shapes of these sources. A number of post-AGB stars have been classified into four classes based on the shape of the SED (VHG89):

- I. Flat spectrum between  $4$  and  $25\mu\text{m}$  and a steep fall-off to shorter wavelengths,
- II. Maximum around  $25\mu\text{m}$  and a gradual fall-off to shorter wavelengths,
- III. Maximum around  $25\mu\text{m}$  and a steep fall-off to a plateau roughly between  $1$  and  $4\mu\text{m}$  with a steep fall-off at shorter wavelengths,
- IV. Two distinct maxima; one around  $25\mu\text{m}$  and a second between  $1$  and  $2\mu\text{m}$  (**IVa**) or one around  $25\mu\text{m}$  and a second  $< 1\mu\text{m}$  (**IVb**).

Here, we adopt the VHG89 classification scheme for the SEDs of our sources. Because only five of our sources were studied in VHG89 with a partial coverage of the stellar component (i.e.,  $> 1\mu\text{m}$ ), we compiled new

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<sup>4</sup>We included four other PPN candidates (one SOLE source, *IRAS* 21282+5050, and three DUPLEX sources, *IRAS* 04395+3601, Red Rectangle (*IRAS* 06176–1036), and Egg Nebula) whose mid-infrared and optical morphologies have been identified.

SEDs of our sources by adding our photometric measurements at optical wavelengths to the latest published data in the literature. Figures 6, 7, and 8 show updated SEDs for SOLE, DUPLEX, and stellar sources, respectively, with VHG class assignments indicated in each frame. The SED shapes of SOLE and DUPLEX nebulae are indeed very distinct from each other, but are very similar within each morphological type of the nebulosity. Stellar sources are of a mix of classes and are discussed in §4.2.5. Table 4 (column 5) summarizes a clear correlation between the morphological and SED classes.

All SOLE nebulae have a double-peaked, class IV SED. The prominent central stars in SOLE nebulae appear in their SED as the well-defined, unobscured optical/near-infrared peak and the thermal emission from the circumstellar dust appears as an almost equal flux peak. There is a subdivision of the SED class among SOLE nebulae depending on the location of the optical/near-infrared peak. The difference stems from the degree of reddening of the central star due to its circumstellar dust/gas shell. Class IVb PPNe tend to have physically larger circumstellar shells and hence their column densities are lower, less dereddening the central star. Interestingly, mid-infrared images are resolved for those of class IVb (*IRAS* 07134+1005, *IRAS* 17436+5003, and *IRAS* 19114+0002), and this coincidence is consistent with the picture of more extended, optically thin dust shells of SOLE nebulae. *IRAS* 21282+5050 is a very young PN that we classify as a SOLE source based on morphology (Kwok, Hrivnak, & Langill 1993, Meixner et al. 1997), but its SED class appears to be III because the shorter wavelengths light from its hot central star (Of7, Cohen & Jones 1987) is more reddened by the dust than the star light from a typical PPN central star.

DUPLEX SEDs are of class II (e.g., *IRAS* 19374+2359) or of class III (e.g., *IRAS* 17150–3224). Both classes II and III are characterized by a prominent far-infrared peak (30 to 50  $\mu\text{m}$ ) with an optical/near-infrared excess that represents the central star or its associated reflection nebulosity. The difference between class II and III SEDs is the presence of a rather large near-infrared excess in class II, which is commonly attributed to either an ongoing mass loss episode or the presence of very compact circumstellar dust shell (VHG89). Interestingly, this SED class difference among DUPLEX sources corresponds to the visibility of the central star. That is, the SED will be of class II when the central star is partially visible whereas it will be of class III when the central star is completely obscured from the view. *IRAS* 09452+1330 is of class I but has a flat peak at  $\lesssim 10\mu\text{m}$  caused by its lower  $T_{\text{eff}}$  ( $\sim 2000\text{K}$ ), which is consistent with its AGB stellar nature. Its very sharp drop into the shortward wavelengths resulted in non-detection in our *B* band image (Table 2). We classify *IRAS* 08005–2356 of class II because of its gradual fall-off in shorter wavelengths due to rather large optical/near-infrared flux. Our classification of *IRAS* 08005–2356 and *IRAS* 17423–1755 being DUPLEX sources is well supported by the resemblance in the shapes of the two SED classes.

The differences in the SED shapes between SOLE and DUPLEX nebulae can be explained in the context of our hypothesis. In the case of a SOLE nebula, the circumstellar dust is optically thin and permits a clear, albeit reddened, view of the central star with a modest amount of dust emission, which is proportional to the column density of dust. Hence, we see two distinct, comparable peaks of stellar and dust emission in its SED. In the case of a DUPLEX nebula, on the other hand, the circumstellar dust is optically so thick that almost all of the star light is absorbed by the dust and is reradiated at mid- to far-infrared wavelengths; only a few optical photons escape through the biconical openings of the dust shell. Therefore, we see a prominent dust emission peak accompanied by an optical/near-infrared plateau in its SED. In the framework of our hypothesis, an inclination angle effect among DUPLEX sources manifests itself as the difference in their SED shapes.

#### 4.2.3. *IRAS/Near-Infrared Two-Color Diagrams*

To demonstrate the differences between SOLE and DUPLEX sources, we use the  $J-K$  vs.  $K-[25]$  diagram, an *IRAS*/near-infrared two-color diagram (Fig. 9). Here,  $[25]$  is *IRAS* flux at  $25\mu\text{m}$  in magnitude converted by  $[25] = -2.5 \log(F_\nu/6.73)$  (*IRAS* Explanatory Supplement 1988). Because  $K-[25]$  color relates the heights of stellar and dust peaks whereas  $J-K$  color describes the shape of the stellar component, the  $J-K$  vs.  $K-[25]$  diagram introduces characteristics of detached dust shells and incorporated the SED dichotomy into a diagram. The robustness of the  $J-K$  vs.  $K-[25]$  diagram is evident in the clear bifurcation between morphological groups. In  $J-K$  color, SOLE sources are bluer ( $\lesssim 1.45$ ) than DUPLEX sources. This bluer color is consistent with the presence of an optically thinner circumstellar shell along the line of sight to the central star. In  $K-[25]$  color, DUPLEX sources are spatially separated according to the visibility of the central star: DUPLEX sources with invisible central stars are redder than SOLE sources while those with partially visible central stars (*IRAS* 08005–2356 and *IRAS* 17423–1755) are bluer than SOLE sources. This bifurcation among DUPLEX sources follows the split of the SEDs into classes II and III: very high near-infrared excess in the class II DUPLEX sources makes their  $K-[25]$  colors bluer than the class III DUPLEX sources and even bluer than SOLE sources. The diagram thus not only signifies the difference between SOLE and DUPLEX sources but also differentiates the partial/total obscuration of the central star in DUPLEX nebulae, and should be a very useful tool in identifying the nature of dust shell by near- to mid-infrared colors.

With new all-sky near-infrared surveys becoming available (e.g. 2MASS and DENIS), near-infrared two-color diagrams will also be a valuable tool in discriminating a particular type of sources from a large data set. Whitelock (1985) presented near-infrared ( $JHK$ ) photometry for 80 PNe and classified them into several types in terms of the visibility of the central star due to dust obscuration and of the location in the near-infrared two-color  $J-H$  vs.  $H-K$  diagram. Since the apparent morphological bifurcation is also partly based on the visibility of the central star, we adopt the classification scheme of Whitelock (1985) and make use of such two-color diagrams. Figure 10 is the  $J-H$  vs.  $H-K$  diagram with our sources that have published near-infrared photometric data. Also shown in the diagram are the regions according to the object classification for PN candidates: Nebula+Star, Nebula, Nebula+Dust, Star+Dust, and Miras (Whitelock 1985). Because of the dusty nature of PPNe, all of our sources are distributed over a linear diagonal region that corresponds to the regions of Miras and Star+Dust objects. There is a parallelism between the distributions of our targets and planetary nebulae in the diagram: SOLE nebulae correspond to PNe with prominently visible central nuclei (Nebula+Star), whereas DUPLEX nebulae correspond to dust enshrouded PNe (Nebula+Dust). There also seems to be a border that separates the region of SOLE sources from that of DUPLEX sources on the region of Miras (dashed line in Fig. 10). All SOLE nebulae are found on or blueward of the border and all DUPLEX nebulae are found on or redward of the border. The fact that DUPLEX sources are redder than SOLE sources suggests that DUPLEX nebulae are associated with a larger amount of obscuring dusts than SOLE nebulae are and this corroborates our hypothesis of the morphological bifurcation being induced by the differing optical thickness in the two types of sources.

#### 4.2.4. *The Inclination Angle Effect*

The inclination angle between the axis of symmetry with the line of sight can change the morphological appearance of an object. We have seriously considered if the inclination angle effect alone could explain all the observed differences between SOLE and DUPLEX nebulae with questions such as if SOLE nebulae are

nearly pole-on DUPLEX nebulae or not. In the following, we discuss that the evidence suggests otherwise.

Suppose that the dust shell structure of all existing PPNe are of DUPLEX type, i.e., all dust shells have the same geometry of optically thick tori. When sources are oriented edge-on ( $90^\circ$  inclination angle), most of the star light is blocked by the dust torus and we observe optical reflection nebulosities in the form of more or less well-balanced bipolar lobes with a dust lane (e.g. *IRAS* 17150–3224 and *IRAS* 17441–2411). However, in other cases when the inclination is in some intermediary angle, sources should appear as imbalanced nebulae either with a dust lane (with larger intermediate inclination angle) or without a dust lane (with smaller intermediate inclination angle), whose central stars are seen off center in the nebulosities when visible. The imbalance in the structure of nebulosities occurs because the far side of the nebulosity (which is pointing away from us) will be at least partially obscured by the near side of the optically thick dust torus, as we see in the images of *IRAS* 08005–2356 and *IRAS* 17423–1755, for example. This imbalance of brightness was also shown in simulated images of *IRAS* 17441–2411 with 4 different inclination angles presented by Su et al. (1998, their Fig. 5). According to their simulation, the central star is seen evidently off-centered even at  $30^\circ$  inclination angle.

As we have seen in our images of SOLE nebulae, 11 of 21 nebulae appear as well-balanced, smooth, and symmetric low surface brightness nebulosities with their central stars located at centers of the nebulae. Following the discussion above, this is possible only when all 11 sources are oriented exactly pole-on or extremely close to pole-on. Thus, if this is the case one has to explain why nearly half the objects are oriented at zero or near-zero inclination angles with respect to us. For instance, *IRAS* 07134+1005 would be a prime example of a PPN viewed nearly exactly pole-on because it shows an extended, almost circular reflection nebulosity of uniform brightness with its central star at the center of the nebulosity. Nevertheless, the mid-infrared images of *IRAS* 07134+1005 clearly show a two-peaked, limb-brightened dust torus which suggests a non-zero inclination angle and radiative transfer calculations support a model of an equatorially enhanced dust torus viewed at an inclination angle of  $\sim 45^\circ$  (Meixner et al. 1997). If *IRAS* 07134+1005 were really a DUPLEX source viewed at a  $45^\circ$  inclination angle, it should have appeared as either an imbalanced nebula with the central star located off center or a bipolar nebula with one of the lobes partially obscured. However, that is not the case and thus the inclination angle effect can not simply explain the data. The most reasonable interpretation of the data is that the optical thickness along the line of sight is too low to cause any detectable difference, which is also supported by radiation transfer calculations (edge-on  $\tau_{9.7\mu\text{m}} \sim 0.03$ , Meixner et al. 1997).

As we have seen in the previous section, the distinction between SOLE and DUPLEX sources is obvious and the subdivision among DUPLEX sources is remarkable in the  $J$ – $K$  vs.  $K$ – $[25]$  diagram (Fig.10). One of the most peculiar aspects of the *IRAS*/near-infrared diagram is that the sources are not distributed linearly as in the  $J$ – $K$  vs.  $H$ – $K$  diagram. If the inclination angle effect were the main cause for the distinction between SOLE and DUPLEX sources, the sources would have been distributed linearly with the region of DUPLEX sources with obscured central stars being located between the regions of SOLE sources and DUPLEX sources without central stars. Alternatively, the absence of subdivision among SOLE sources corroborates our view of SOLE sources being associated with optically thin dust tori: no matter what the inclination angle is there is no partial obscuration in the SOLE sources and they cluster as a single group in the  $J$ – $K$  vs.  $K$ – $[25]$  diagram.

It is of course possible that we come across a source whose orientation is exactly or very close to pole-on. In such cases, how the reflection nebulosities appear is not trivial. No matter to which morphological type a source belongs, it is incredibly difficult to detect reflection nebulosity when the source is viewed pole-on because the central star appears extremely prominent and the prominent PSF spikes are likely to

severely obscure the nebulosity. The appearance of *IRAS* 07430+1115, a SOLE PPN, does not fall into the morphological type of the DUPLEX nebulae, but the source still looks different from other SOLE nebulae. Although SED and two-color diagrams also suggest that this object is a SOLE source, it is possible that this is a DUPLEX source oriented at or very close to pole-on. However, we tentatively classify the source as a SOLE nebula and will not delve into the issue in this study. The pole-on cases must be further investigated with at least two-dimensional calculations. Radiative transfer calculations with fully axisymmetric models would clarify these inclination angle effects with more certainty and such calculations will be the focus of our future work.

#### 4.2.5. *Non-Association with Nebulosities*

There are six sources we tentatively classify as stellar sources because no reflection nebulosities are detected. Neither PSF subtraction nor deconvolution achieves the perfect removal of the WFPC2 diffraction features, and thus, there are always some residual diffraction artifacts which can mask a low surface brightness reflection nebula. In particular, our observations are insensitive to circular nebulosities with extremely low surface brightness, which can be easily confused with the WFPC2 circular diffraction wings.

When viewed pole-on, SOLE sources would appear more or less like stellar sources due to a combined effect of the high star-to-nebula contrast and a confusion with the WFPC2 PSF artifact. For example, *IRAS* 04386+5722 and *IRAS* 05113+1347 may be such cases. The images of these sources barely show nebulosities and the deconvolved images are almost nebula-free for *IRAS* 04386+5722 whereas suggestive of a compact nebula for *IRAS* 05113+1347. However, their SEDs are of class IVa (Fig. 8) and their locations in two-color diagrams are within the region of SOLE sources (an asterisk and a filled star in Figures 9 and 10). The slight offset of *IRAS* 04386+5722 towards blue in  $K-[25]$  color in the  $J-K$  vs.  $K-[25]$  diagram can be explained considering the pole-on inclination angle effect: the source is of SOLE type and hence the stellar emission peak is present in the SED irrespective of the angle of inclination and hence its  $J-K$  color would not be very different from other SOLE sources, while its  $K-[25]$  color can be bluer than other SOLE sources because the stellar emission would be more prominent than other SOLE sources with respect to the dust emission. *IRAS* 05113+1347 is located among other SOLE sources.

*IRAS* 10158–2844 and *IRAS* 15465+2818 have very bright central stars, but the amount of far-infrared excess is smaller (Fig. 8). The lack of far-infrared excess in these sources makes the SED classification scheme of VHG89 inapplicable and also makes both have much bluer  $K-[25]$  color than other sources ( $K-[25] = 3.48$  and  $3.12$ , respectively). This is consistent with the evolutionary status of these R Coronae Borealis stars, in which they have had little recent mass loss but are associated with very diffuse, extended circumstellar dust shells (Gillett et al. 1986, Waters et al. 1989). However, if we consider the stellar component peaks alone (which peak at  $< 1\mu\text{m}$ ) these objects will be found among DUPLEX sources (Fig. 10; filled stars in the region of DUPLEX sources) suggesting the presence of circumstellar dust rather close to the central star, on-going mass loss, or pole-on inclination angle effects. The nature of variability of *IRAS* 10158–2844 is suspected to be due to variable obscuration by circumstellar material along the line of sight and the inclination angle of this source is expected to be  $\gtrsim 50^\circ$  (Waelkens et al. 1991). In fact, both of these sources show indications of a very recent mass loss (Clayton et al. 1997, Meixner et al. 1999). Hence, a possible explanation for the non-detection of any nebulosities is that the column density of dust near the star in these sources is much lower than in SOLE sources.

*IRAS* 20043+2653 is classified as an OH/IR source (cf. García-Lario et al. 1997a), and hence, the

central star is likely be in the AGB or extreme AGB phase. This interpretation fits well with the SED shape and its very red  $H-K$  color (both of which resemble to those of *IRAS* 09452+1330, an extreme AGB star). Therefore, the absence of any reflection nebulosity seems to suggest that *IRAS* 20043+2653 has not yet developed one. *IRAS* 22142+5206 is classified as a young stellar object embedded in a massive CO molecular cloud of  $\sim 7300M_{\odot}$  (Dobashi et al. 1998). Its SED shows significant far-infrared excess without a stellar component (Fig. 8), which is a signature of a class I young stellar object (e.g., Wilking, Lada, & Young 1989). Its location in two-color diagrams is also consistent with the young stellar object interpretation.

### 4.3. Origins of the PPN Morphological Bifurcation

The origin of axisymmetry in many astrophysical systems is always of a great importance and there have been numerous possible mechanisms for the creation of nebular morphologies (cf. Livio 1997). Instead of reviewing every possible means, we will focus on the origins of the differing equatorial density enhancement in the SOLE and DUPLEX nebulae.

#### 4.3.1. Galactic Height and Progenitor AGB Stellar Mass

One of the strongest pieces of circumstantial evidence that is related to the morphological bifurcation is probably that bipolar nebulae are preferentially found close to the plane of the Galaxy. With a large sample of PNe, Corradi & Schwartz (1995) found that bipolar PNe were distributed closer to the Galactic plane (scale height  $z_h = 130$  pc with  $|z| \lesssim 850$  pc) than elliptical PNe ( $z_h = 325$  pc with  $|z| \lesssim 1300$  pc). Following this finding, they suggested that bipolar PNe have evolved from more massive progenitors than elliptical PNe, adopting a lower limit of  $1.5M_{\odot}$  for the bipolar PN progenitors. This correlation is also suggested by the galactic latitudes and the  $|z|$  values of our sources (Table 4). DUPLEX sources, having a mean height of 220 pc with a range of  $|z| \lesssim 520$ , are more confined to the Galactic plane than the SOLE sources, which have a mean height of 470 pc with a range of  $|z| \lesssim 2100$ . Although a direct comparison between our values (mean Galactic heights) to the values obtained by Corradi & Schwartz (1995; Galactic scale heights) is not possible, there certainly exists a parallelism in the ways these two types of PPNe and two types of PNe are distributed in the Galaxy. To test if the Galactic height distributions of the SOLE and DUPLEX sources are not exactly equal, we calculated the Kolmogorov–Smirnov (K–S) statistic (0.417) and its significance level (0.186). This means that there is 18.6% chance that the K–S statistic, the greatest difference between the two cumulative distribution functions of the Galactic heights, will be smaller than 0.417, if both types of objects are from the same Galactic height distribution. Considering the fact that some SOLE sources do exist close to the Galactic plane where DUPLEX sources are populated, the outcome of the K–S test is suggestive that SOLE and DUPLEX sources are not distributed in the exactly same manner. Therefore, it is likely that more massive progenitor AGB stars lead to DUPLEX PPNe and that bipolar PNe are the direct descendants of DUPLEX PPNe and elliptical PNe are the SOLE PPN offspring. In fact, this is a very reasonable result in the context of stellar evolution. The majority of AGB stars become white dwarfs of roughly  $0.6 M_{\odot}$  (Schönberner 1981); the more massive the progenitor, the more material the star has to dump into the circumstellar environment. Therefore, PPNe from more massive progenitor AGB stars are likely to have more obscuring material in the circumstellar shell, which could completely block the central star from the observer’s view as in DUPLEX nebulae. This is well demonstrated in Figure 10 as DUPLEX sources being redder than SOLE sources. Also consistent with the division of PPN into two classes is that

the degree of equatorial enhancement and the subsequent evolution depend on the fundamental parameters of the central star, especially, the stellar mass.

#### 4.3.2. Circumstellar Chemistry

Because PPNe can be put into two groups in terms of photospheric and/or circumstellar chemistry (C- or O-rich), we looked for a correlation between the circumstellar chemistry and morphological bifurcation. When referring to the chemical type of a PPN, one needs to be cautious because a PPN can have both C- and O-rich characteristics in the circumstellar environment above the photosphere (e.g., *IRAS* 08005–2356 and Red Rectangle). The circumstellar chemistry can be determined mainly by the presence of a certain molecular species (e.g., OH in an O-rich shell, Hu et al. 1994; HCN in a C-rich shell, Loup et al. 1993) or some infrared spectral feature (e.g.,  $9.7\mu\text{m}$  feature in an O-rich shell;  $21\mu\text{m}$  feature in a C-rich shell, Kwok, Volk, & Hrivnak 1989). On the other hand, the photospheric chemistry can be determined by direct abundance measurements (e.g., *IRAS* 02229+6208, *IRAS* 07430+1115, Reddy, Bakker & Hrivnak 1999; *IRAS* 04296+3429, Decin et al. 1998; *IRAS* 05341+0852, Reddy et al. 1997; *IRAS* 06530–0213, Reddy 1999; *IRAS* 18095+2704, Klochkova 1995; *IRAS* 19114+0002, Reddy & Hrivnak 1999; *IRAS* 20462+3416, García-Lario et al. 1997a) or the presence of optical photospheric features of  $\text{C}_2$  or  $\text{C}_3$  molecules (e.g., Hrivnak 1995). Comparison between the PPN morphology and photospheric/circumstellar chemistry does not seem to yield any apparent correlation between the two. Table 4 (column 7) summarizes the non-correlation between morphology and chemistry.

#### 4.3.3. Stellar Ages

It may be possible to attribute the differing optical thickness in SOLE and DUPLEX PPNe to their ages. PPN dust shells expand with time and older shells tend to have smaller optical depth, and therefore, DUPLEX PPNe are expected to be younger than SOLE PPNe. If one insists on a single evolutionary channel, DUPLEX PPNe may be forerunners of SOLE PPNe. However, bifurcating PPNe into SOLE and DUPLEX types by their ages does not appear to be possible because of the spectral types of these stars. If DUPLEX PPNe were indeed younger than SOLE PPNe, DUPLEX PPNe would have had the latest spectral types possible (G to M types) and SOLE PPNe would have had the earliest spectral types (A to F types). However, SOLE PPNe include a number G types (e.g. *IRAS* 04296+3429) and DUPLEX PPNe include F types (e.g. *IRAS* 08005–2356 and Egg Nebula). Given the horizontal evolutionary track in the HR diagram during the PPN phase and its surpassingly short evolutionary time scale, it is not possible to conclude one type of PPNe is younger than the other.

### 4.4. From the Dual PPN Morphology to the PN Morphology

During the PPN phase, the two-layered PPN shell keeps expanding around the central post-AGB star while the surface temperature of the star continues to rise. A fast wind initiates somewhere along the PPN phase and pushes the inner boundary of the PPN shell out to typical PN dimensions, while shaping the boundary geometry and increasing the boundary density (Kwok 1982). The central post-AGB star finally becomes hot enough to emit photoionizing photons, which illuminate the inner boundary of the circumstellar gas shell as a PN. Because we observe dust-scattered light in PPNe and ionized gas emission

in PNe, we can not trivially link the PPN and PN morphologies via a mere resemblance in the images. We can, nevertheless, interpolate the PPN and PN morphologies considering the circumstellar distribution of matter and see the PN morphological structures (round, elliptical, and butterfly classes; Balick 1987) in the dual PPN morphology. The bipolar shapes of DUPLEX PPNe (e.g., *IRAS* 08005–2356, *IRAS* 17150–3224) may be forerunners to the bipolar PNe (e.g., Hourglass Nebula, Sahai & Trauger 1995). The simply elongated SOLE nebulae (e.g., *IRAS* 17436+5003, *IRAS* 20462+3416) may be precursors of elliptical PNe (e.g., NGC 3132 (HST Heritage Team 1998), IC 3568 (Bond & Ciardullo 1997)). The multi-lobed SOLE nebulae (e.g., *IRAS* 22272+5435, *IRAS* 06530–0213) may be progenitors of complex PNe (e.g., Stingray Nebula (Bobrowsky et al. 1998), Cat’s Eye Nebula (Harrington & Borkowski 1995)). We thus see that the development of the PPN axisymmetry in the superwind phase probably sets the stage for the emergence of axisymmetry in PNe. Jet-like structures, however, are rather rare in PPNe (e.g., *IRAS* 17423–1755, which is a young PN) and this may suggest that the formation of jet-like structures seen in PNe (e.g., NGC 5307, Bond & Ciardullo 1997) does not share the same generating mechanism as the PPN axisymmetric structures.

## 5. Conclusions

After observing 27 PPN candidates with *HST*, we have found elongated low surface brightness reflection nebulosities around 21 sources. We have also found that an optical reflection nebulosity can manifest itself in the form of a faint, elliptically elongated shell in addition to the bipolar form. The PPN circumstellar shell seems to be intrinsically axisymmetric (ellipticity  $\sim 0.44$ ) and we argue that the axisymmetry emerges in the superwind phase, the latter of the two-phased AGB mass loss epoch. A morphological bifurcation exists among the PPN nebulosities: of 21 extended nebulae, 11 are SOLE nebulae (e.g., *IRAS* 07134+1005) and 10 are DUPLEX nebulae (e.g., *IRAS* 17150–3224). We discuss how the morphological dichotomy is caused by the difference in optical thickness of the PPN circumstellar dust shells: SOLE shells are optically thin whereas a DUPLEX shells are optically thick. The distinctness between SOLE and DUPLEX nebulae in terms of optical thickness of the dust shells is evidenced by the correlation between the mid-infrared morphology of dust emission regions and optical morphology of reflection nebulosities, the characteristic shapes of the SEDs, and the near- and *IRAS*/near-infrared two-color diagrams. We also discuss that the inclination alone may not be able to explain the well-balanced shape of reflection nebulosities with their central stars seen at the center. Although we find no correlation between the circumstellar chemistry and morphology, we do find that DUPLEX sources tend to be found closer to the Galactic plane than SOLE sources. This suggests that DUPLEX PPNe probably originate from higher mass AGB progenitor stars than SOLE PPNe. The origins of the apparent morphological bifurcation – the equatorial density enhancement in the superwind – remain inconclusive. In addition to optical imaging of reflection nebulosities, direct, high-resolution imaging of dust emission regions in mid-infrared wavelengths will be extremely important in studies of PPNe because optical images of reflection nebulosities alone are not sufficient to decipher the orientation of these objects. Similarly, future investigation will have to require at least two-dimensional, radiative transfer model calculations.

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calibrating and analyzing data from *HST*. STSDAS includes the same calibration routines as are used in the routine data processing pipeline, as well as general-purpose tools and enhancements to the Image Analysis and Reduction Facility (IRAF) distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. This research also made use of the SIMBAD database, operated at CDS, Strasburg, France. Ueta and Meixner are supported by NASA Grants GO-06737.01-95A and GO-06364.02-95A and NSF Career Award Grant AST 97-33697. Bobrowsky is supported by STScI Grants GO-06364.01-94A and GO-006737.02-95A. We are thankful for the help that Chris Skinner gave us in setting up these observations. Chris J. Skinner, who died suddenly in October 1997, was a valued colleague and friend. We would also like to thank the STScI support staff for their guidance in setting up these observations and helping with the reduction of the data.

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Fig. 1.— (a)–(c): Images of SOLE nebulae in the increasing order of their right ascension (north is up and east is left): the left-most frame shows the *IRAS* ID and scale of the object. The tick marks show relative offsets in arcseconds. The filter types are shown at the bottom of each frame with “+ RL” indicating Richardson-Lucy deconvolution. Wedges show the ranges of log-scaled flux density to help readers visually illustrate the emission contrast. See Table 1 for the star-to-nebula surface intensity ratio.

Fig. 2.— (a)–(c): Images of DUPLEX nebulae. The displaying scheme follows Figure 1. See Table 2 for the star-to-nebula surface intensity ratio.

Fig. 3.— Selected Images of stellar sources. These images exemplify how PSF artifacts appear in both reduced and deconvolved images. The basic displaying scheme follows Figure 1.

Fig. 4.— A schematic diagram illustrating the essential difference between SOLE and DUPLEX sources. [Top] In the SOLE sources, the superwind mass loss creates marginally equatorially enhanced dust shell (gray area near the central star) within a spherically symmetric the AGB wind shell. Because the axisymmetric dust shell is *optically thin*, it permits star light to leak out in all directions (arrows), creating an elliptically elongated nebula (dashed line) with the bright central star. [Bottom] In the DUPLEX sources, the superwind mass creates highly equatorially enhanced dust shell (black area near the central star) within a spherically symmetric the AGB wind shell. Because the axisymmetric dust shell is *optically thick*, it permits starlight to leak out only along the biconical openings of the dust torus (arrows), creating a bipolar, dumbbell-like nebulosity (dashed perimeter) with the partially or completely obscured central star. Relative sizes of components are not to scale.

Fig. 5.— Composites of optical and mid-infrared images of four PPN candidates. Mid-infrared contours are overlaid onto an optical grayscale image. The top row shows examples of the SOLE-toroidal correlation (*IRAS* 07134+1005: F410M and  $11.8\mu\text{m}$  and *IRAS* 17436+5003: F410M and  $12.5\mu\text{m}$ ) and the bottom row shows examples of the DUPLEX-core/elliptical correlation (*IRAS* 17150–3224: F814W and  $12.5\mu\text{m}$  and *IRAS* 16342–3814: F814W and  $9.8\mu\text{m}$ ). Tickmarks show relative offsets from the center.

Fig. 6.— Spectral energy distributions of SOLE sources in  $\lambda F_\lambda$  ( $\text{ergs s}^{-1} \text{ cm}^{-2}$ ) vs.  $\lambda$  ( $\mu\text{m}$ ). The name of the source and its SED class assignment (Van der Veen, Habing & Geballe 1989; see text) are given in each frame. Photometric data are taken from our measurements and references listed in Table 4.

Fig. 7.— Spectral energy distributions of DUPLEX sources in  $\lambda F_\lambda$  ( $\text{ergs s}^{-1} \text{ cm}^{-2}$ ) vs.  $\lambda$  ( $\mu\text{m}$ ). Conventions follow those of Fig. 6.

Fig. 8.— Spectral energy distributions of stellar sources in  $\lambda F_\lambda$  ( $\text{ergs s}^{-1} \text{ cm}^{-2}$ ) vs.  $\lambda$  ( $\mu\text{m}$ ). Conventions follow those of Fig. 6.

Fig. 9.— *IRAS*/Near-infrared two-color ( $J-K$  vs.  $K-[25]$ ) diagram for our sources. Circles, triangles, and stars are respectively SOLE, DUPLEX, and stellar sources. The asterisk is *IRAS* 04386+5722, a stellar source whose chemistry is undetermined. The numbers associated with symbols refer to the source numbers given in Table 4 (column 1). Two stellar sources, *IRAS* 10158–2844 and *IRAS* 15465+2818, and one DUPLEX source, *IRAS* 09452+1330, are located off the diagram:  $(K-[25], J-K) = (3.48, 1.59)$ ,  $(3.12, 2.11)$ , and  $(10.21, 6.54)$ , respectively. This diagram displays the color of the star vs. the ratio of the dust peak to the stellar peak in the SED. Sources are more clearly clustered into three groups: SOLE and DUPLEX sources with a totally obscured central star (w/o Star), and DUPLEX sources with a visible central star (w/ Star). Each subdivision is labeled in the diagram. The dashed line indicates a fiducial division between SOLE and DUPLEX sources. All sources above the line are of DUPLEX type and below the line are of SOLE type.

Fig. 10.— Near-infrared two-color ( $J-H$  vs.  $H-K$ ) diagram for our sources. Conventions follow those of Fig. 9. Two AGB stars, *IRAS* 09452+1330 (C-rich) and *IRAS* 20043+2653 (O-rich) are located off the diagram:  $(H-K, J-H) = (3.03, 3.51)$  and  $(2.79, 0.30)$ , respectively. Whitelock’s classification of planetary nebula (1985) is also shown in the diagram: the regions of Nebula+Star, Nebula+Dust, Star+Dust, Nebula, and Miras. Sources are clustered diagonally in the diagram, which indicates the black-body temperature decreasing to the upper right. The dashed line indicates a fiducial division between SOLE and DUPLEX sources. All sources on the right of the line are of DUPLEX type and on the left of the line are of SOLE type.

TABLE 1  
OBSERVED AND DERIVED PROPERTIES OF SOLE NEBULAE

IRAS ID	Obs. Coord. (J2000)		WFPC2 Filter	$F_{\lambda}$ <sup>1</sup>	<i>HST</i> Mag <sup>2</sup>	Surface Intensity <sup>3</sup>		Size (" $\times$ " ( $\sigma$ ))	Ellipticity <sup>4</sup> ( $e = 1 - b/a$ )
	RA	DEC				Peak <sup>3a</sup>	Ratio <sup>3b</sup>		
02229+6208	02:26:41.9	+62:21:22	F555W	6.36 e−14	11.89	9.2 e−2	1000	2.09 $\times$ 1.42 (2.2)	0.32
			F814W	3.51 e−13	10.04	5.1 e−1	1200	2.14 $\times$ 1.52 (2.5)	0.29
04296+3429	04:32:57.0	+34:36:13	F555W	7.68 e−15	14.19	2.0 e−3	65	1.88 $\times$ 1.57 (2.9)	0.61, 0.67
			F814W	2.54 e−14	12.89	1.4 e−2	220	1.69 $\times$ 1.59 (3.0)	0.61, 0.66
05341+0852	05:36:55.0	+08:54:08	F555W	1.43 e−14	13.51	1.9 e−2	220	1.12 $\times$ 0.81 (5)	0.72, 0.33
			F814W	3.16 e−14	12.65	4.8 e−2	440	1.14 $\times$ 0.78 (5)	0.70, 0.31
06530−0213	06:55:31.8	−02:17:29	F555W	8.83 e−15	14.03	8.3 e−3	390	2.36 $\times$ 1.11 (2.5)	0.53
			F814W	3.14 e−14	12.66	3.4 e−2	860	2.33 $\times$ 0.92 (2.2)	0.61
07134+1005 (HD56126)	07:16:10.3	+09:59:48	F410M	1.03 e−12	8.87	1.5 e+0	5300	4.73 $\times$ 4.15 (5.3)	0.12
			F547M	1.71 e−12	8.32	4.0 e+0	11000	4.70 $\times$ 3.71 (4.0)	0.21
07430+1115	07:45:51.4	+11:08:20	F555W	3.90 e−14	12.42	1.9 e−2	18	1.01 $\times$ 0.90 (6)	0.11
			F814W	7.45 e−14	11.72	5.4 e−2	50	0.98 $\times$ 0.86 (7)	0.12
15436+5003 (HD161796)	17:44:55.4	+50:02:40	F410M	8.07 e−12	6.63	1.4 e+1	9400	4.34 $\times$ 2.46 (4.9)	0.43
			F547M	5.82 e−12	6.99	1.0 e+1	7100	4.49 $\times$ 2.53 (3.6)	0.44
18095+2704 (OH53.8+20.2)	18:11:30.8	+27:05:15	F555W	2.74 e−13	10.30	2.9 e−1	960	1.89 $\times$ 1.27 (2.2)	0.80, 0.54
			F814W	3.70 e−13	9.98	4.8 e−1	1100	1.82 $\times$ 1.04 (6)	0.69, 0.60
19114+0002 (HD179821)	19:13:58.6	+00:07:32	F410M	7.11 e−13	9.27	2.0 e+0	180000	10.69 $\times$ 8.30 ( $\sim$ 1)	0.22
			F547M	1.70 e−12	8.32	3.0 e+0	110000	10.82 $\times$ 8.52 (2)	0.21
20462+3416	20:48:16.6	+34:27:25	F555W	1.45 e−13	10.99	4.4 e−1	17000	4.10 $\times$ 3.23 (2.2)	0.21
			F814W	6.05 e−14	11.95	1.4 e−1	16000	3.99 $\times$ 2.94 (2.5)	0.26
22272+5435 (HD235858)	22:29:10.4	+54:51:07	F555W	1.28 e−12	8.63	1.7 e+0	3500	3.53 $\times$ 3.47 (5.6)	0.43, 0.61
			F814W	2.26 e−12	8.01	2.6 e+0	3700	3.47 $\times$ 3.37 (4.0)	0.41, 0.62

<sup>1</sup>In units of ergs/s/cm<sup>2</sup>/Å.

<sup>2</sup>*HST* WFPC2 system magnitudes (STMAG).

<sup>3</sup>In units of ergs/s/cm<sup>2</sup>/Å/sr: 3a-peak intensity of the central source, 3b-star-to-nebula intensity ratio.

<sup>4</sup> $a$  and  $b$  are respectively major and minor axis lengths.

TABLE 2  
OBSERVED AND DERIVED PROPERTIES OF DUPLEX SOURCES

<i>IRAS</i> ID	Obs. Coord. (J2000)		WFPC2 Filter	$F_{\lambda}$ <sup>1</sup>	<i>HST</i> Mag <sup>2</sup>	Surface Intensity <sup>3</sup>		Size ( $'' \times ''$ ( $\sigma$ ))	Ellipticity <sup>4</sup> ( $e = 1 - b/a$ )			
	RA	DEC				Peak <sup>3a</sup>	Ratio <sup>3b</sup>					
08005–2356	08:02:40.8	–24:04:44	F555W	1.01 e–13	11.38	1.1 e–1	990	$2.68 \times 1.42$ (2.3)	0.47			
			F814W	1.91 e–13	10.70	2.5 e–1	1200	$2.58 \times 1.13$ (1.6)	0.44			
09452+1330 (IRC+10216)	09:47:57.4	+13:16:43	F450W	...	...	...	...	...	...			
			F814W	5.37 e–15	14.54	2.0 e–3	250	$3.12 \times 3.00$ ( $\sim 1$ )	0.04			
17423–1755 (Hen3-1475)	17:45:14.2	–17:56:47	F555W	2.59 e–14	12.87	5.8 e–3	1900	$3.75 \times 1.98$ (5) <sup>i</sup>	0.47			
			F814W	3.78 e–14	12.46	2.2 e–2	10000	$3.70 \times 2.19$ (3) <sup>i</sup>	0.41			
19374+2359	19:39:35.6	+24:06:28	F555W	2.39 e–16	17.96	2.4 e–5	32	$3.29 \times 1.63$ (2.6)	0.50			
			F814W	1.89 e–15	15.71	3.5 e–4	130	$3.07 \times 1.57$ (4)	0.49			
16342–3814	16:37:39.9	–38:20:17	F555W	2.02 e–15	15.64	...	...	$2.55 \times 0.71$ (3)	0.72			
			Eastern Lobe	...	1.22 e–16	18.68	7.1 e–5	9	$0.52 \times 0.39$ (3)	0.25		
			Western Lobe	...	1.74 e–15	15.80	9.2 e–4	120	$1.27 \times 0.71$ (3)	0.44		
			F814W	5.99 e–15	14.46	...	...	$2.71 \times 0.82$ (3)	0.70			
			Eastern Lobe	...	8.81 e–17	19.04	2.7 e–4	8	$0.76 \times 0.56$ (2)	0.26		
			Western Lobe	...	5.12 e–15	14.63	1.3 e–3	50	$1.29 \times 0.82$ (2)	0.36		
			F450W	3.26 e–15	15.12	...	...	$12.59 \times 6.12$ (5)	0.51			
			Southeastern Lobe	...	9.51 e–16	16.45	1.6 e–5	10	$2.70 \times 1.22$ (10)	0.55		
17150–3224	17:18:19.7	–32:27:21	Northwestern Lobe	...	2.44 e–15	15.43	4.9 e–5	32	$2.57 \times 1.37$ (10)	0.47		
			F814W	1.24 e–14	13.07	...	...	$8.96 \times 4.72$ (3)	0.47			
			Southeastern Lobe	...	9.23 e–15	13.99	1.9 e–4	170	$2.51 \times 1.61$ (5)	0.36		
			Northwestern Lobe	...	1.11 e–14	13.78	2.3 e–4	210	$2.50 \times 1.39$ (5)	0.44		
			F450W	1.04 e–15	16.35	...	...	$4.43 \times 1.76$ (2)	0.60			
			Northern Lobe	...	6.11 e–16	16.93	4.2 e–5	5	$1.61 \times 0.90$ (3)	0.44		
			Southern Lobe	...	3.29 e–16	17.61	1.7 e–5	2	$1.43 \times 0.57$ (3)	0.60		
			F814W	6.98 e–15	14.29	...	...	$6.47 \times 3.77$ (5)	0.42			
17441–2411	17:47:13.5	–24:12:50	Northern Lobe	...	5.18 e–15	14.61	3.0 e–4	28	$1.28 \times 0.80$ (10)	0.38		
			Southern Lobe	...	3.50 e–15	15.04	1.2 e–4	11	$1.46 \times 0.44$ (10)	0.70		
			F555W	3.60 e–16	17.51	...	...	$3.48 \times 2.11$ (3)	0.39			
			Northern Lobe	...	1.26 e–17	21.15	2.0 e–7	1	$0.74 \times 0.70$ ( $\sim 1$ ) <sup>ii</sup>	0.05		
			Southern Lobe	...	3.52 e–16	17.53	6.7 e–5	330	$1.71 \times 1.27$ (7)	0.26		
			F814W	1.19 e–15	16.21	...	...	$4.42 \times 3.13$ (3)	0.29			
			Northern Lobe	...	4.25 e–17	19.83	2.4 e–6	1	$1.69 \times 1.11$ (5) <sup>ii</sup>	0.34		
			Southern Lobe	...	1.18 e–15	16.22	1.7 e–4	70	$0.14 \times 0.48$ (5)	0.71		
22574+6609	22:59:18.3	+66:25:47	F555W	1.16 e–17	21.24	6.3 e–6	6	$0.82 \times 0.50$ (4.7)	0.39			
			F814W	1.16 e–16	18.74	3.5 e–5	12	$0.73 \times 0.48$ (2)	0.34			
			23321+6545	23:34:23.1	+66:01:51	F555W	3.15 e–18	22.65	1.3 e–5	9	$0.26 \times 0.16$ (8)	0.38
						F814W	1.06 e–17	21.34	3.1 e–5	12	$0.40 \times 0.35$ (5)	0.13

<sup>1</sup>In units of ergs/s/cm<sup>2</sup>/Å.

<sup>2</sup>*HST* WFPC2 system magnitudes (STMAG).

<sup>3</sup>In units of ergs/s/cm<sup>2</sup>/Å/sr: 3a-peak intensity of the central star or lobe, 3b-star- or peak-to-nebula intensity ratio.

<sup>4</sup> $a$  and  $b$  are respectively major and minor axis lengths.

<sup>i</sup>Associated with point symmetric jets which extend 16''.70 in V and 16''.92 in I.

<sup>ii</sup>The northern lobe appears to have an oblate shape.

TABLE 3  
OBSERVED AND DERIVED PROPERTIES OF STELLAR SOURCES

<i>IRAS</i> ID	Obs. Coord. (J2000)		WFPC2 Filter	$F_{\lambda}$ <sup>1</sup>	<i>HST</i> Mag <sup>2</sup>	Surface Peak Intensity <sup>3</sup>
	RA	DEC				
04386+5722	04:42:49.0	+57:27:47	F555W	1.63 e−14	13.37	5.1 e−2
			F814W	2.09 e−13	10.60	4.2 e−1
05113+1347	05:14:07.8	+13:50:28	F555W	3.68 e−14	12.49	4.8 e−2
			F814W	9.15 e−14	11.50	1.3 e−1
10158−2844 (HR4049)	10:18:07.6	−28:59:32	F469N	2.44 e−11	5.43	6.7 e+1
15465+2818 (RCrB)	15:48:34.4	+28:09:25	F469N	1.56 e−12	8.42	5.4 e+0
20043+2653	20:06:22.7	+27:02:32	F555W	> 7.39 e−16	< 16.73	> 8.6 e−4
			F814W	> 8.36 e−16	< 16.59	> 4.8 e−4
22142+5206	22:16:10.1	+52:21:13	F555W	> 1.83 e−15	< 15.74	> 7.7 e−4
			F814W	> 1.52 e−15	< 15.95	> 7.4 e−4

<sup>1</sup>In units of ergs/s/cm<sup>2</sup>/Å.

<sup>2</sup>*HST* WFPC2 system magnitudes (STMAG).

<sup>3</sup>In units of ergs/s/cm<sup>2</sup>/Å/sr.

TABLE 4  
OPTICAL VS. MID-INFRARED MORPHOLOGIES AND OTHER PROPERTIES OF PPN CANDIDATES

#	IRAS ID	Object Type	Mid-IR Morph. <sup>i</sup>	SED Type	Spectral Class	Chem <sup>ii</sup> (* /CS)	$b^{\text{iii}}$ (deg)	$z^{\text{iii}}$ (pc)	References <sup>iv</sup>
<b>SOLE SOURCES</b>									
1	02229+6208	PPN	unknown	IVa	G8-K0Ia	C/C	1.5	60	<b>22,48,52</b>
2	04296+3429	PPN	unresolved	IVa	G0Ia	C/C	-9.1	650	1,8, <b>12,19,20,23,31,37,44,46,47,53,62</b>
5	05341+0852	PPN	unresolved	IVa	G20-Ia	C/C	-12.2	2100	<b>1,12,15,22,46,48,53,54</b>
6	06530-0213	PPN	unresolved	IVa	F0Iab	C/C?	-0.1	4	<b>12,28,29,48,50,53</b>
7	07134+1005	PPN	toroidal	IVb	F5Iab	C/C	10.0	520	1,5,23, <b>25,33,35,36,37,44,46,47,62</b>
8	07430+1115	PPN	unresolved	IVa	G50-Ia	C/C	17.1	90	<b>12,22,23,31,48,52</b>
16	17436+5003	PPN	toroidal	IVb	F3Ib	O/O	30.9	620	1,5,11,23, <b>25,30,43,44,45,48,56,62</b>
18	18095+2704	PPN	unresolved	IVa	F3Ib	O/O	20.2	660	5, <b>12,23,24,26,33,34,40,44,48,62,63</b>
19	19114+0002	PPN?	toroidal	IVb	G5Ia	O/O	-5.0	350	5,18,23, <b>25,32,44,51,62,63</b>
23	20462+3416	PN	...	IVb	B1Ia	O/..	-5.8	290	<b>12,13,49,59</b>
25	22272+5435	PPN	toroidal	IVa	G2Ia	C/C	-2.5	130	1, <b>12,14,19,21,23,37,44,46,47,62,63,67</b>
	21282+5050	PN	toroidal	III	..	C/C	-0.1	6	47,69,70
<b>DUPLEX SOURCES</b>									
9	08005-2356	PPN	unresolved	II	F5e	C/O	3.6	250	<b>11,19,29,31,58,62</b>
10	09452+1330	AGB	...	I	C9.5	C/..	45.1	140	<b>1,6,40,44,57,62</b>
13	16342-3814	AGB	core/elliptical	III	M	.. /O	5.8	220	<b>12,17,42,48,55,63</b>
14	17150-3224	PPN	core/elliptical	III	G2	.. /O	3.0	130	<b>12,17,27,28,29,38,39,44,48,53,63,66</b>
15	17423-1755	PN	...	II	..	.. /O	5.8	510	<b>12,61</b>
17	17441-2411	PPN	unknown	III	..	.. /C?	2.2	110	3,4, <b>12,28,29,38,44,48,53,60,63,66</b>
20	19374+2359	PPN	core/elliptical	II	..	.. /O	1.0	90	<b>26,29,34,40,48,63</b>
21	20028+3910	PPN	unresolved	II/III	..	.. /C	4.1	240	<b>26,29,44,48</b>
26	22574+6609	PPN	unresolved	II	..	C/C	6.0	520	<b>20,26,29,48</b>
27	23321+6545	PPN	unresolved	II/III	..	.. /C	4.3	..	<b>29,44,48</b>
28	04395+3601	PN	core/elliptical	III	B0	C/C	-6.5	190	<b>20,74</b>
29	06176-1036	PPN	core/elliptical	III	B8V	C/O	-11.8	70	<b>68,73</b>
30	AFGL 2688	PPN	core/elliptical	III	F5Iae	C/C	-6.5	140	<b>71,72</b>
<b>STELLAR SOURCES</b>									
3	04386+5722	PPN	unresolved	IVa	M	.. /..	7.5	..	<b>22,48,52</b>
4	05113+1347	PPN	unresolved	IVa	G8Ia	C/C	-14.3	1200	<b>1,9,11,12,19,23,36,48</b>
11	10158-2844	RCrB	unresolved	..	B9.5Ib-II	C/..	22.9	270	<b>1,48,62,64,65</b>
12	15465+2818	RCrB	unresolved	..	F0-F8pe	C/..	51.0	1500	<b>7,10,48,62</b>
22	20043+2653	AGB	unresolved	I	..	O/..	-2.7	..	<b>46</b>
24	22142+5206	YSO	unresolved	II	..	C/..	-3.6	280	<b>9,46,48</b>

<sup>i</sup>Marginally resolved sources have an inconclusive “unknown” morphology classification (Meixner et al. 1999).

<sup>ii</sup>Chemistry: \*—Photosphere, CS—Circumstellar shell

<sup>iii</sup>Galactic latitude,  $b$ , is used with the averaged distance in the literature to estimate the Galactic height,  $z$ .

<sup>iv</sup>References: Photometric data are obtained from references in **boldface**; 1.Bakker et al. 1997, 2.Blommaert et al. 1993, 3.Bobrowsky et al. 1995, 4.Borkowski et al. 1997, 5.Bujarrabal et al. 1992, 6.Campbell et al. 1976, 7.Clayton et al. 1997, 8.Decin et al. 1998, 9.Dobashi et al. 1999, 10.Feast et al. 1997, 11.García-Lario et al. 1990, 12.García-Lario et al. 1997a, 13.García-Lario et al. 1997b, 14.Geballe et al. 1992, 15.Geballe et al. 1990, 16.Gillett et al. 1986, 17.Gütler et al. 1996, 18.Hawkins et al. 1995, 19.Hrivnak 1995, 20.Hrivnak et al. 1991a, 21.Hrivnak et al. 1991b, 22.Hrivnak et al. 1999a, 23.Hrivnak et al. 1994, 24.Hrivnak et al. 1988, 25.Hrivnak et al. 1989, 26.Hrivnak et al. 1999b, 27.Hu et al. 1993a, 28.Hu et al. 1993b, 29.Hu et al. 1994, 30.Humphreys et al. 1974, 31.Iyengar et al. 1997, 32.Kastner et al. 1995, 33.Klochkoova 1995, 34.Kwok et al. 1987, 35.Kwok et al. 1990, 36.Kwok et al. 1995, 37.Kwok et al. 1989, 38.Kwok et al. 1996, 39.Kwok et al. 1998, 40.Lawrence et al. 1990, 40.Le Bertre 1988, 42.Likkel et al. 1988, 43.Likkel et al. 1987, 44.Loup et al. 1993, 45.Luck et al. 1991, 46.Manchado et al. 1989 47.Meixner et al. 1997, 48.Meixner et al. 1999, 49.Parthasarathy 1993, 50.Reddy 1999, 51.Reddy et al. 1999a, 52.Reddy et al. 1999b, 53.Reddy et al. 1996, 54.Reddy et al. 1997, 55.Sahai et al. 1999, 56.Skinner et al. 1994, 57.Skinner et al. 1998, 58.Slijkhuis et al. 1991, 59.Smith et al. 1994, 60.Su et al. 1998, 61.te Lintel Hekkert 1991, 62.TDG94, 63.VHG89, 64.Waelkens et al. 1991, 65.Waters et al. 1989, 66.Weintraub et al. 1998, 67.Zács et al. 1995, 68.Cohen et al. 1975, 69.Cohen et al. 1987, 70.Kwok et al. 1993, 71.Sahai et al. 1998, 72.Skinner et al. 1997, 73.Waters et al. 1998, 74.Westbrook et al. 1975